1 MW Proton Beam for Neutrinos

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Motivation

- Develop an alternative plan to provide high intensity proton beams for the neutrino program beyond 2010
- The plan needs to have the following important features
  - It must be inexpensive
  - It must be completed quickly
  - It should not shutoff the collider complex or the neutrino program for an extended period of time.
- These goals can be accomplished only if:
  - It uses the present Fermilab infrastructure (tunnel enclosures, service buildings, power, utilities, etc.)
  - The project is staged
- After the collider program concludes, the present antiproton production complex can be converted into a multi-stage proton accumulator for injection into the Main Injector.
  - Accumulator -> Momentum Stacker
  - Recycler -> Box Car Stacker

Motivation

- Slip stacking multiple Booster batches in either the Main Injector or the Recycler is the central concept for reaching beam powers up to 700kW
  - Longitudinal stacking at 8 GeV reduces the peak intensity requirement in the Booster
  - Results in a smaller required aperture for the Booster
    - Smaller space charge tune shift
    - Reduced requirements on acceleration efficiency
- Above 700kW, the number of batches stacked into the Recycler can not be increased further by slip stacking because of the rather severe amount of emittance dilution that is fundamental to the slip stacking process.
- Momentum Stacking has much smaller longitudinal emittance dilution than slip stacking and can be used in place of slip stacking to achieve beam powers greater than 700kW

Beams Document 1782

A 2 Megawatt Multi-Stage Proton Accumulator

1 Introduction

1.1 Motivation

The delivery of high intensity proton beams for neutrino experiments is a core element of the Fermilab physics program for the next decade and beyond. This document outlines a plan which will greatly enhance the intensity capability beyond the year 2010 should budget and approval for the Proton Driver Linac fail to materialize. In order to reduce costs and to minimize disruption to the ongoing program, the plan uses existing infrastructure (tunnel enclosures, service buildings, power, utilities, etc.). The cost scale is estimated to be less than \$100M, and the plan could be fully implemented by 2012 without the need for an extended shutdown period.

The use of existing infrastructure allows the plan to be broken into stages. Project staging has the important benefit of providing a fraction of the total performance at a fraction of the total cost. The schedule for each stage is driven by physics need and funding availability.

1.2 Concept

Multi-turn injection into the Booster is the current process for obtaining high intensity proton bunches in the Main Injector for neutrino experiments. Because of the relatively small aperture of the Booster and the large space charge tune shift at Booster injection, proton loss at injection limits the number of protons per bunch. Since space charge effects rapidly decrease with energy, it is more desirable to increase the proton intensity at higher energies. Due to the rapid cycling nature of the Booster, many Booster batches can be quickly combined at the Booster extraction energy. Because the bunch length requirements for neutrino experiments are not strict, the best technique to combine multiple Booster batches is to coalesce them longitudinally.

Slip stacking multiple Booster batches is the central concept of the Proton Plan[1]. In Stage 1, while the collider program is still running, nine Booster batches will be slipped stacked in the Main Injector for the neutrino program. In Stage 2, when the Recycler becomes available after the collider program is concluded, the slip stacking will be done in the Recycler which can handle 33% more batches with a 30% decrease in the cycle time. The number of batches stacked into the Recycler can not be increased further by slip stacking because of the rather severe amount of emittance dilution that is fundamental to the slip stacking process.

Another large increase in proton intensity is possible after the collider program concludes because the present antiproton production complex can be converted into a multi-stage proton accumulator for injection into the Main Injector. This accumulator would have three major components, each re-using or replacing existing machines:

- The Accumulator ring as a RF momentum stacker.
- The Recycler ring as a box-car stacker.
- The Debuncher ring would be replaced with a wide aperture booster.

1.2.1 RF Momentum Stacking in the Accumulator

The center piece of this concept is RF momentum stacking in the Accumulator. The key features of RF momentum stacking are a large momentum aperture and injection system located at high dispersion. Because the same features are required for stochastic momentum stacking of antiprotons, RF momentum stacking in the Accumulator would be possible with only minor modifications to the Accumulator.

During momentum stacking, a Booster batch is placed on the injection orbit of the Accumulator and accelerated towards the high energy aperture as shown in Figure 1-1. Another Booster batch is injected onto the injection orbit and accelerated towards the high energy aperture and deposited adjacent to the previous batch. The limit to how many Booster batches can be stacked is not the Accumulator aperture but the momentum aperture of the Main Injector at the transition energy. With present Booster performance, the Main Injector momentum aperture can comfortably handle over four Booster batches. This large number of batches can be combined using momentum stacking because momentum stacking has very little longitudinal emittance dilution.

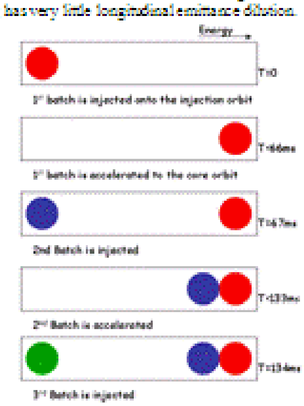

Figure 1-1 Cross-section of the transverse aperture in high dispersion of the Accumulator during momentum stacking.

1.2.2 Box Car Stacking in the Recycler

Once at least three to four Booster batches have been momentum stacked in the Accumulator, the coalesced proton stack would be transferred to the Recycler. Since the Accumulator circumference is one seventh of the Recycler circumference, five more Accumulator stacks can be placed one after the other in the Recycler (box-car style) while leaving one seventh of the ring as an abort gap. The Recycler fully loaded in this manner would contain twenty four Booster batches which is twice the number of batches

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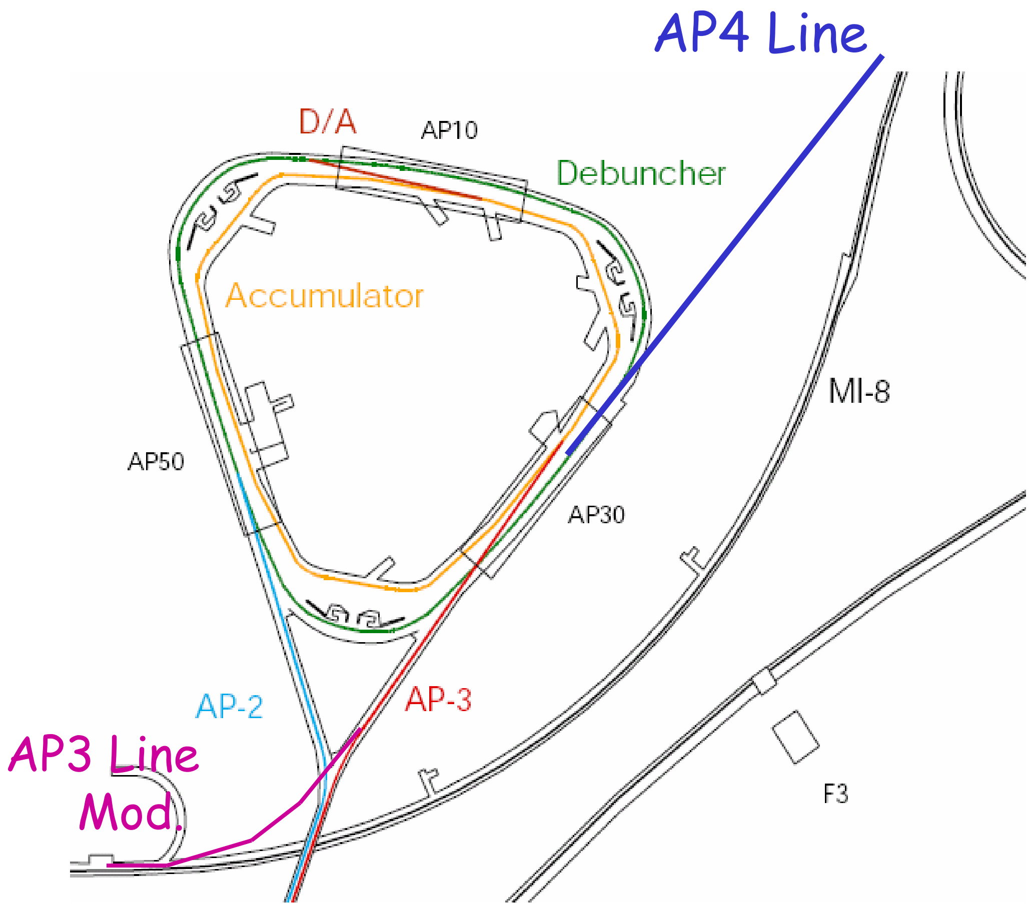
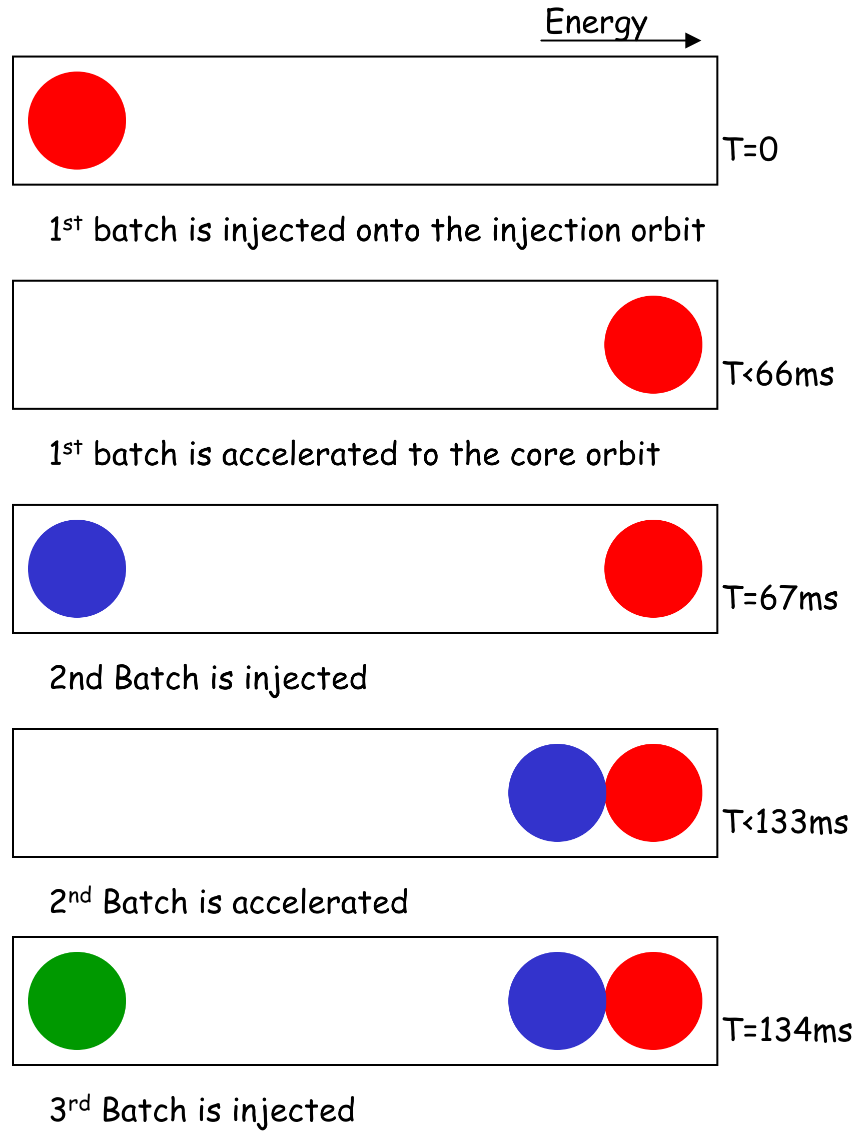
Concept - Momentum Stacking in the Accumulator

- After acceleration in the Booster, the beam will be transferred DIRECTLY to the Accumulator ring
- The Booster is connected to the Accumulator via a re-built AP4 Line
- The new AP4 line is about 240 meters in length
  - Use magnets from the AP2 line for 8 GeV operation
  - Civil Construction 4.5 M$
- The AP3 line needs to be connected to the MI-8 line
  - The modification is about 100 meters in length
    - Use magnets from the rest of AP3
    - Civil Construction 3 M$



Mechanics of Momentum Stacking

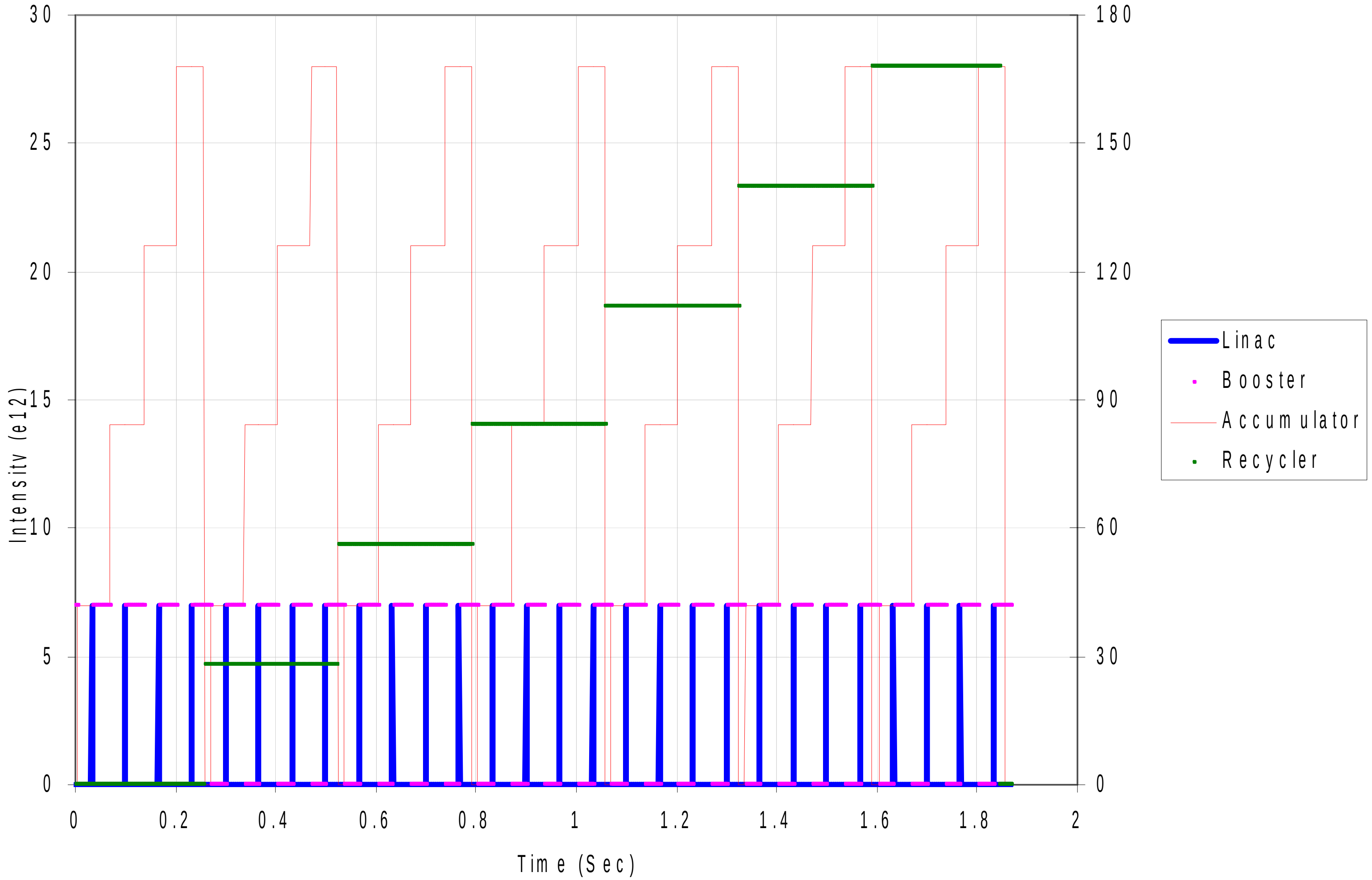
- The Accumulator was designed for momentum stacking
  - ➢ Large momentum aperture ~ 84 x 2.8 eV-Sec
  - ➢ Injection kickers are located in 9m of dispersion
  - ➢ Injection kickers do not affect core beam
- Inject in a newly accelerated Booster batch every 67 mS onto the low momentum orbit of the Accumulator
- The freshly injected batch is accelerated towards the core orbit where it is merged and debunched into the core orbit
- Momentum stack 3-4 Booster batches



Multi-stage Proton Accumulator Scheme

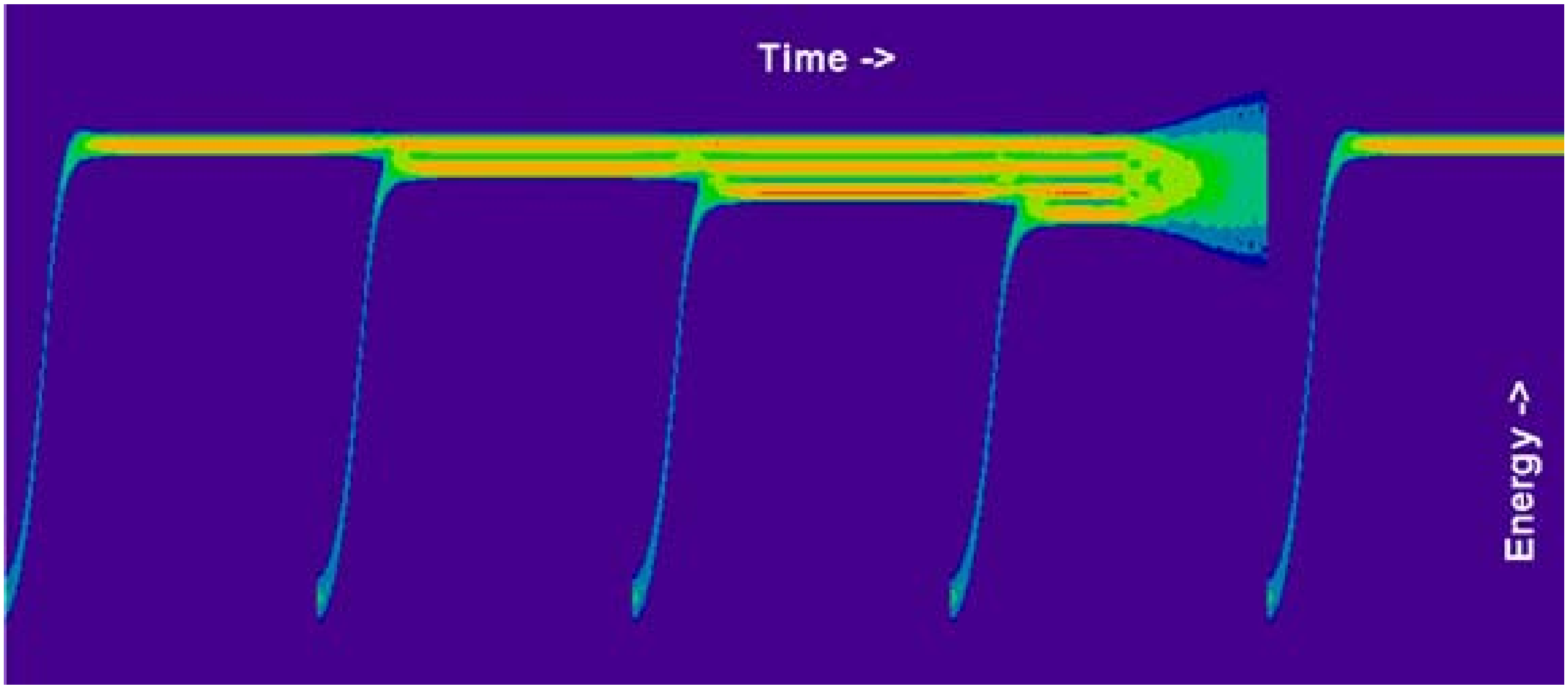
- Momentum stack in the Accumulator
  - Inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the Accumulator
  - Decelerate new batch towards core orbit and merge with existing beam
  - Momentum stack 3-4 Booster batches
  - Extract a single Accumulator batch
    - Every 200 – 270 mS
    - At an intensity of 3-4x a single Booster batch
- Box Car Stack in the Recycler
  - Load in a new Accumulator batch every 200-270mS
  - Place six Accumulator batches sequentially around the Recycler
- Load the Main Injector in a single turn

Multi-stage Proton Accumulator Production Cycle



Momentum Stacking

Output longitudinal emittance = 84 * 0.38 eV-sec

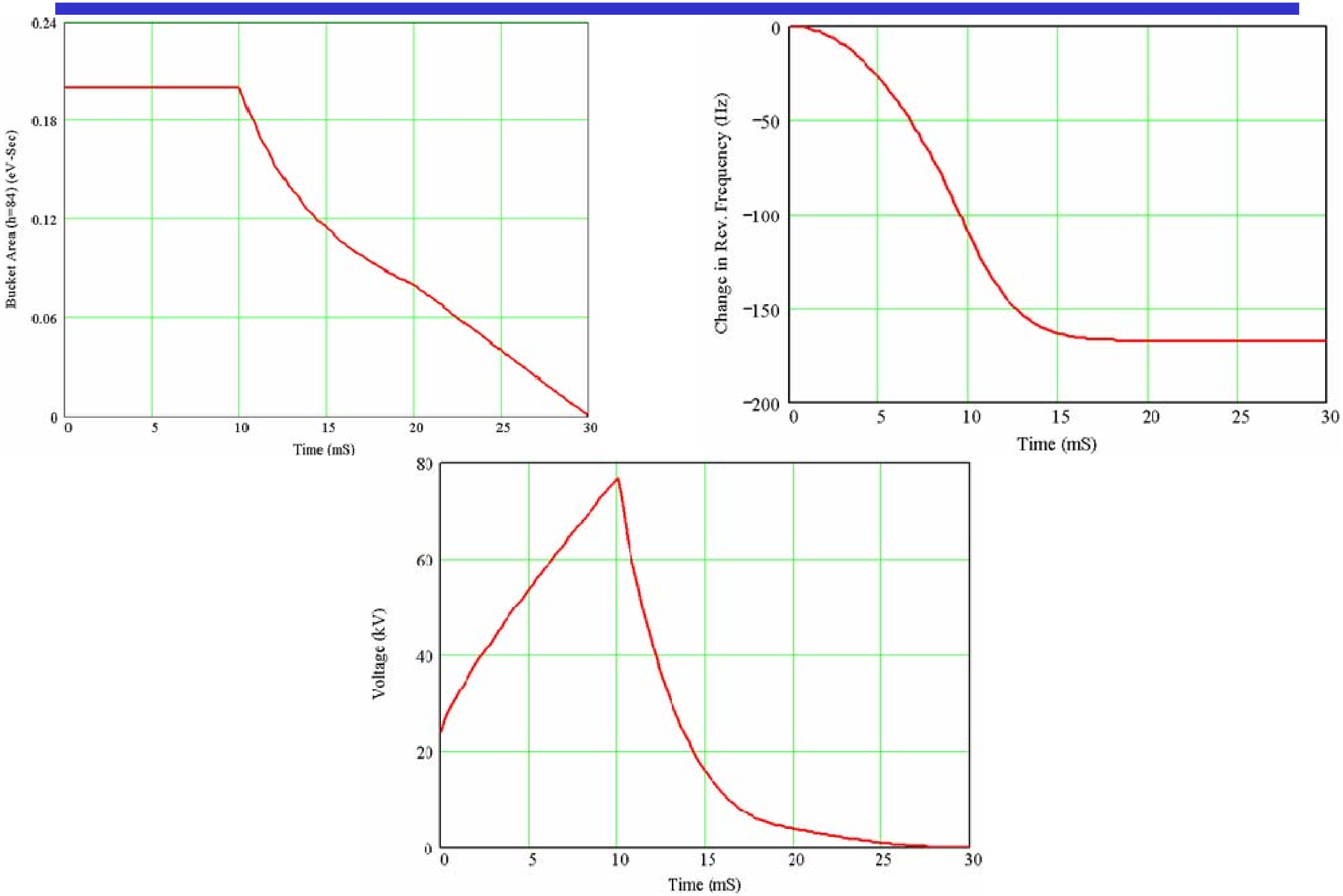


Input longitudinal emittance = 84 * 0.08 eV-sec

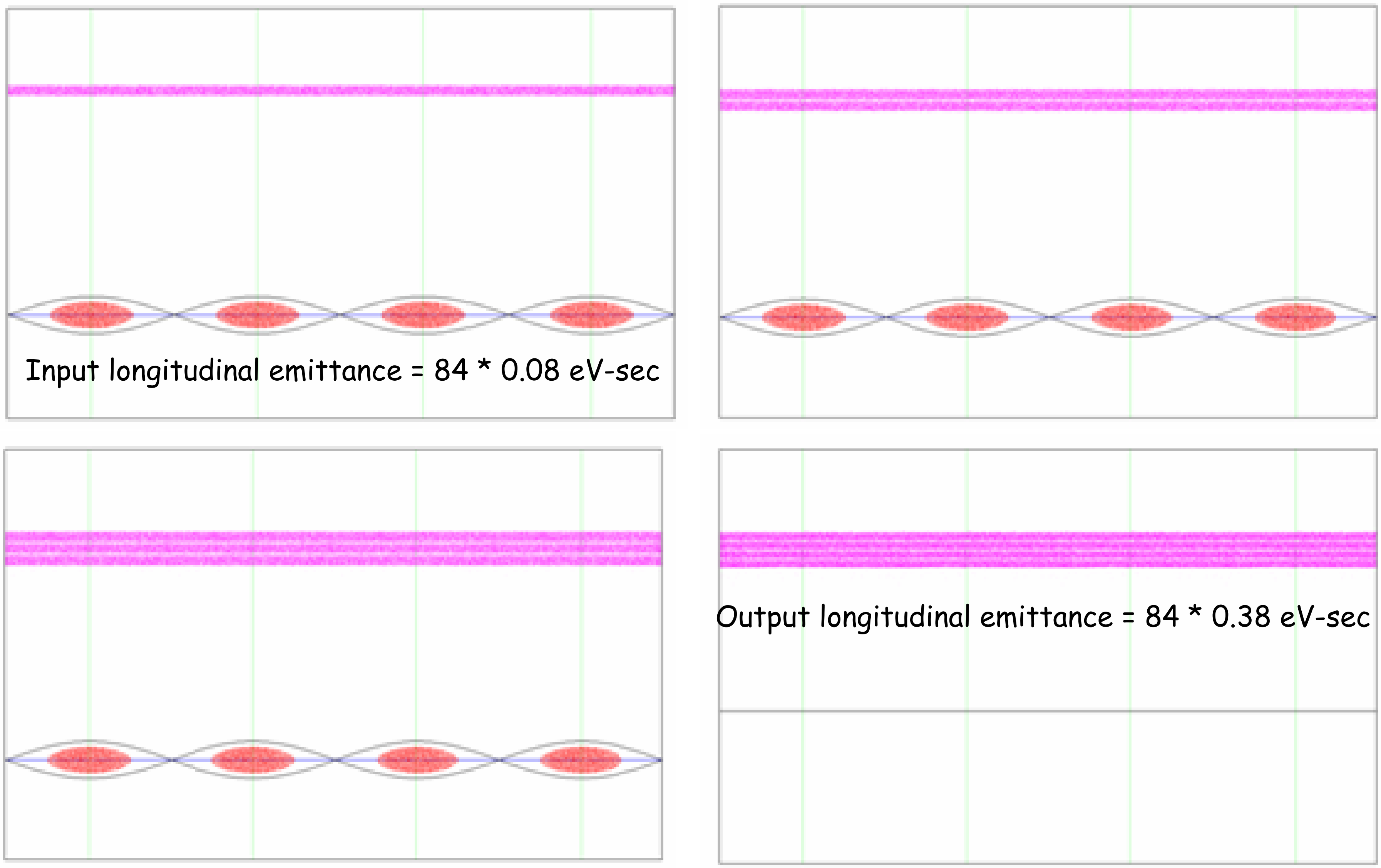
Advantages of Momentum Stacking

- Transient Beam Loading
  - Slip stacking or barrier bucket stacking requires manipulating intense beams with low RF voltages in a mostly empty circumference
  - In momentum stacking, the circumference is always uniformly loaded
- Speed of process
  - Injected beam can be decelerated quickly towards the core beam
- Longitudinal emittance dilution
  - The core beam can be debunched during stacking process reducing the amount of "white spaces"
- Cogging in the Booster
  - Prior to injection into the Accumulator, the injection orbit of the Accumulator is empty
  - The Accumulator injection system can be phase-aligned to the Booster which eliminates cogging in the Booster
  - The Booster notch can be made in the Linac

Momentum Stacking RF Curves



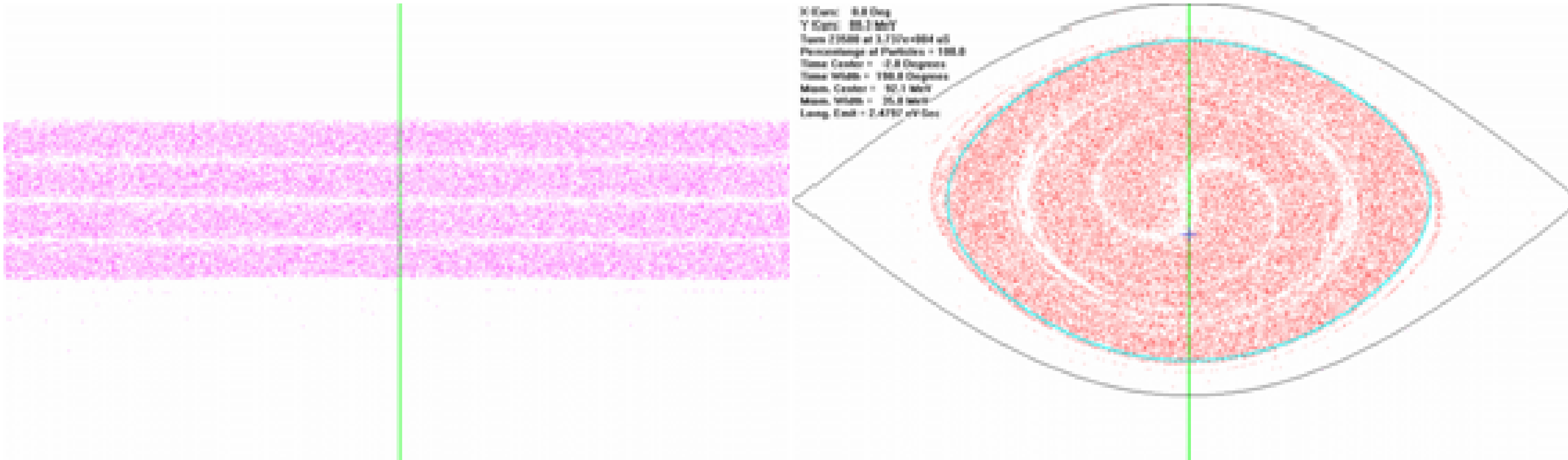
Momentum Stacking Phase Space

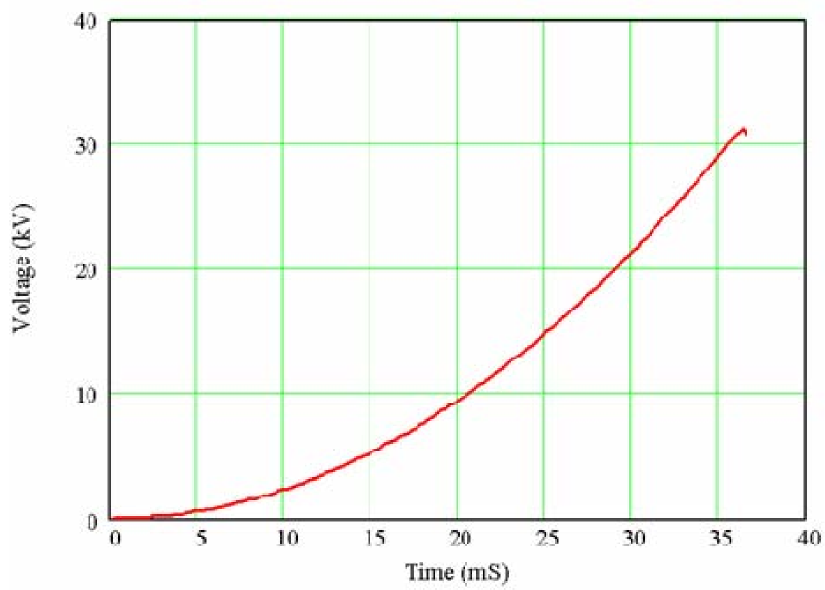


Extraction From the Accumulator

- After 3-4 batches have been stacked begin preparing to extract all the beam from the Accumulator to the Recycler
- Re-bunch the entire stacked beam at h=12 in the Accumulator (7.5 MHz)
  - Low harmonic for a large enough gap between buckets which could accommodate kicker rise time
  - High harmonic for fast synchrotron period for the speed of the process
  - New system –need 30 kV/Turn in Accumulator

Extraction Phase Space





Box Car Stacking in the Recycler

- After 3-4 booster batches have been momentum stacked in the Accumulator, the beam would be transferred to the Recycler.
  - 7.5 MHz MHz synchronous transfer
    - New system
    - Need 80kV/Turn for a 4.2 eV-sec bucket
  - Accumulator phase ALIGNED to the Recycler
- The Accumulator is 1/7 of the Recycler's circumference
- Boxcar stack six of the Accumulator batches leaving 1/7 of the Recycler ring for an abort gap.
- After 6 Accumulator batches have been stacked into the Recycler debunch 7.5 MHz beam in >80mS
- Re-capture in 53 MHz buckets for acceleration.
  - Need 500 kV for 0.6 eV-sec
  - 53 MHz RF system will be installed for slip stacking in the Recycler for the 700kW stage.

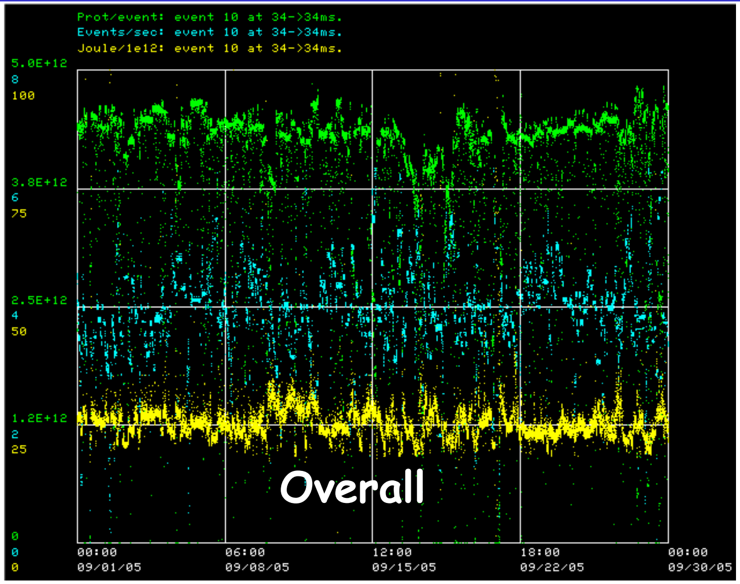
Booster Throughput Scenarios

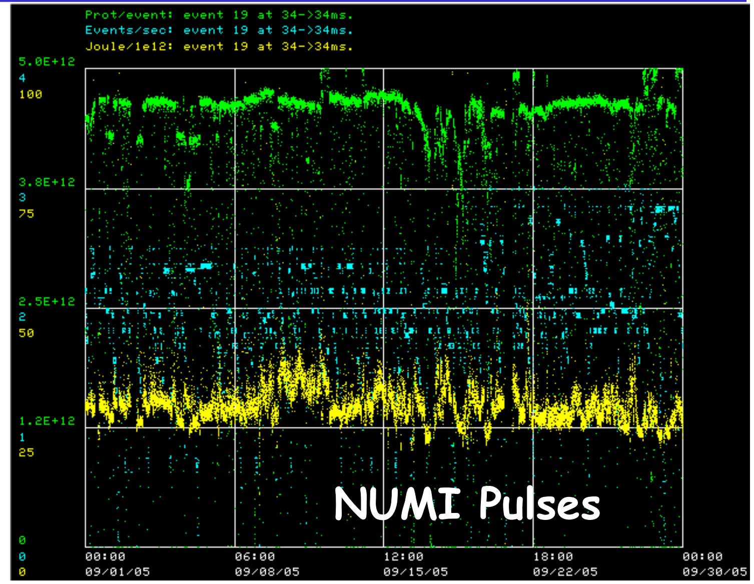
- All the Main Injector Intensity upgrades rely on increased Booster throughput

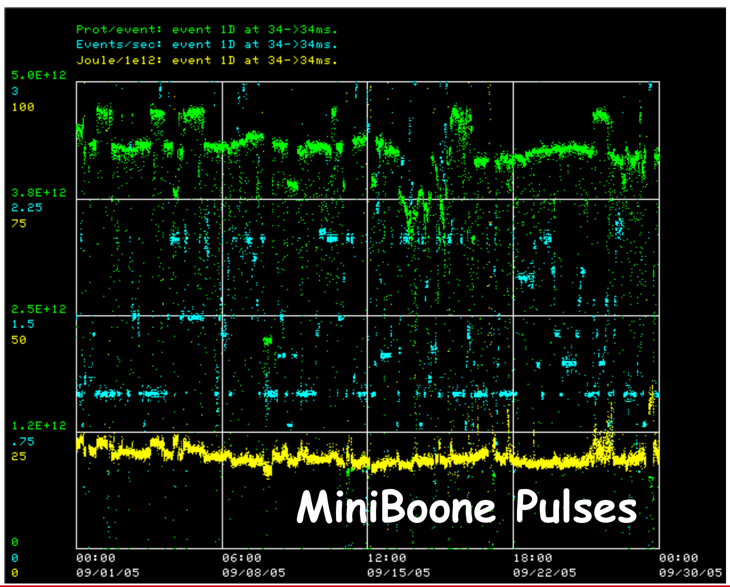
Parameter	Sept. 2005	400kW	700kW	1100kW	1200kW	PD2	
Booster Flux	6.4	13.0	14.1	21.8	23.9	36.4	$x10^{16}$/Hr
Collider Flux	1.1	1.5	0.0	0.0	0.0	0.0	$x10^{16}$/Hr
NUMI Flux	3.2	7.1	14.1	21.8	23.9	36.4	$x10^{16}$/Hr
NUMI Beam Power	162	372	735	1152	1260	1920	kW
MiniBoone Flux	2.1	4.4	0.0	0.0	0.0	0.0	$x10^{16}$/Hr

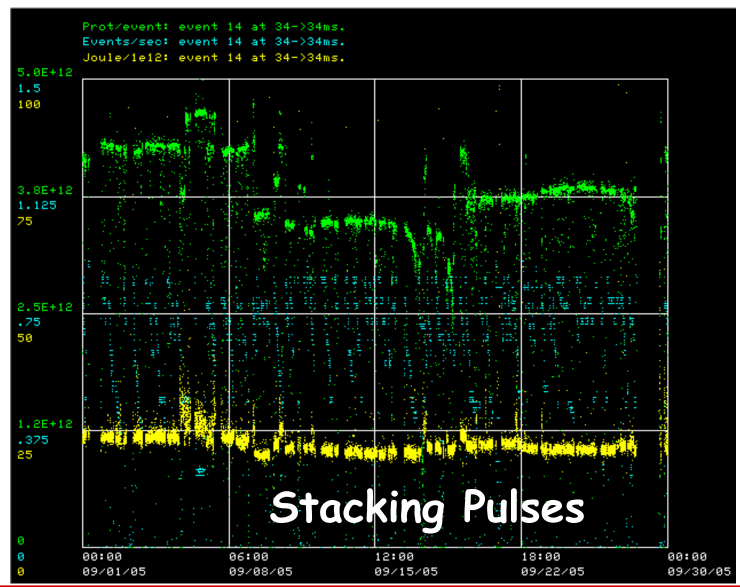
Parameter	Sept. 2005	400kW	700kW	1100kW	1200kW	PD2	
Collider Final Intensity	6.9	8	0	0	0	0	$x10^{12}$
NUMI Final Intensity	22	40	51	80	105	150	$x10^{12}$
MI Cycle Time	2.60	2.07	1.33	1.33	1.60	1.50	Sec
Collider Batches	2	2	0	0	0	0	
NUMI Batches	5	9	12	18	24	6	
Slip Stack Efficiency	88	93	100	100	100	100	%
NUMI Efficiency	95	97.5	97.5	99	99	99	%

Booster Performance Sept. 2005









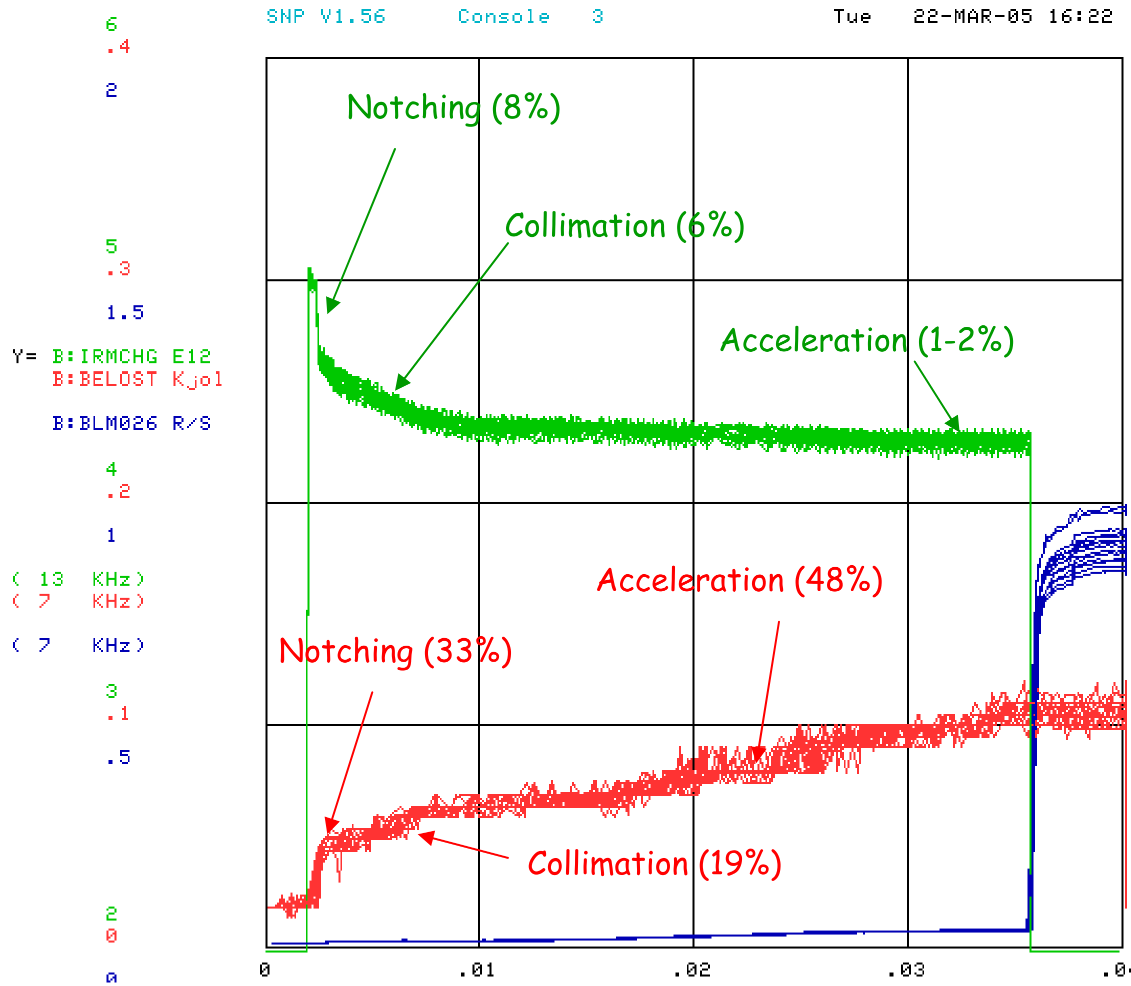
Booster Efficiency

- Amount of beam power lost per pulse is inversely proportional to the repetition rate

$$P_L = J_L R$$

- For simplicity the beam loss can be divided into two categories,
  - beam loss due to creating the beam gap (notch) for extraction
  - beam lost transversely during acceleration

$$J_L = E_n \Delta N_n + E_A \Delta N_A$$



Booster Efficiency

- The total efficiency of the Booster is:

$$\frac{N_{ext}}{N_{inj}} = (1 - f_n - f_A)$$

  - f_n is the ratio of the amount of beam loss during notching to the injection intensity
  - f_A is the ratio of the amount of beam loss during acceleration to the injection
- For a given notching fraction, the fraction of beam loss during acceleration that can be tolerated is:

$$f_A = \frac{P_L - (N_{ext} E_n R + P_L) f_n}{N_{ext} E_A R + P_L}$$

- Assuming a guassian profile as a simple approximation, the amount of beam in the halo that is outside the aperture is:

$$f_h = e^{-3\frac{A}{\varepsilon 95}}$$

Booster Efficiency

- The amount of beam that is permitted to be in the halo is:

$$f_h = \frac{\Delta N_A}{2\left(N_{ext} + \Delta N_A\right)} = \frac{f_A}{2\left(1 - f_n\right)}$$

- The aperture required is :

$$A = \frac{S_f\, \varepsilon_{95}}{3} \ln\left(\frac{2\left(1 - f_n\right)}{f_A}\right)$$

- The half-aperture of the magnets is proportional to
  - The transverse acceptance,
  - The momentum acceptance
  - The closed orbit displacement

$$\Delta x = \sqrt{\frac{A_n}{\beta\gamma}\beta_{max}} + \frac{\Delta p}{p} D_{max} + \text{c.o.d.}$$

- Compare designs with the same space charge tune shift

$$\varepsilon_n \propto \frac{N_{inj}}{\beta\gamma^2 \Delta\nu}$$

Booster Throughput Scenarios

- The vertical aperture in the present Booster is
  - 1.64 inches for the F magnets
  - 2.25 inches for the D magnets
- The horizontal good field aperture is
  - 4.3 inches for the F magnets
  - 3 inches for the D magnets
- The RF cavities in the Booster are located between two D magnets
  - The horizontal beta function is at a minimum
  - The vertical beta function is a maximum.
  - The RF cavity aperture is 2.25 inches.
- To increase Booster throughput, we have two knobs available
  - Increase beam power lost in the Booster tunnel
  - Increase the effective Booster aperture (or decrease the closed orbit distortion tolerance)

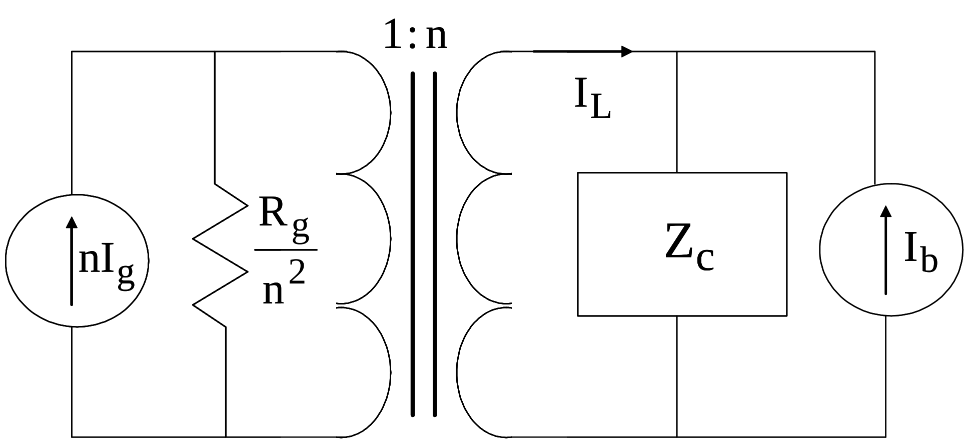
Booster Intensity and Aperture Requirements

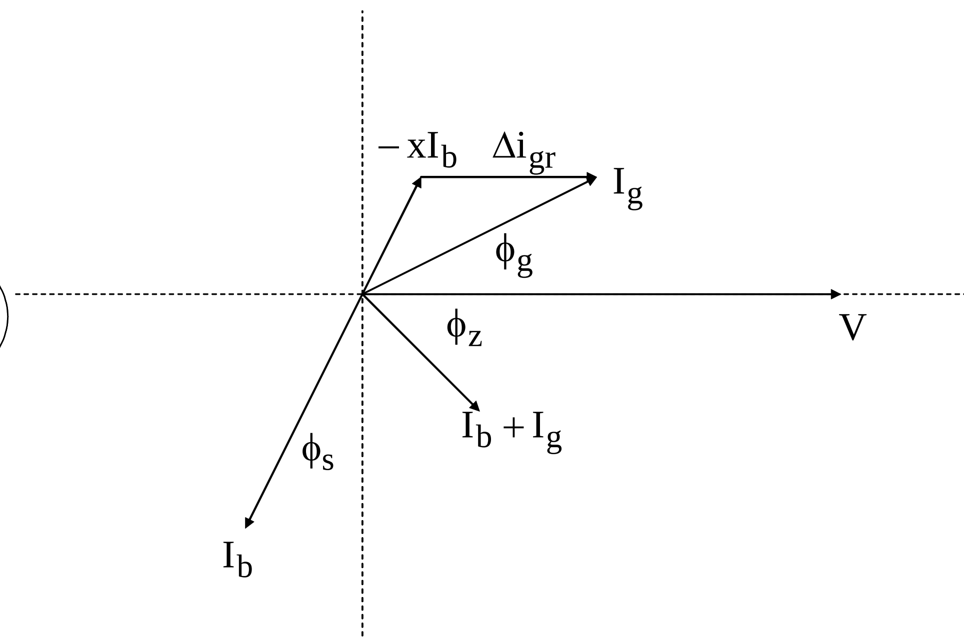
Parameter	Sept. 2005	400kW	700kW	1100kW	1200kW	PD2	
Extraction Intensity	4.4	4.5	4.4	4.5	4.4	25.3	$x10^{12}$
Rep. Rate	4	8	9	13.5	15	4	Hz
Average Beam Power Lost	440	440	440	440	440	440	Watts
Notch Bunches	7	4	4	0	0	2	
Notch Energy	450	450	450	450	450	650	MeV
Acceleration Loss Energy	1050	1050	1050	1050	1050	1050	MeV
Injection Energy	400	400	400	400	400	600	MeV
Allowed Tune Shift	0.47	0.47	0.47	0.47	0.47	0.47	
Bunching Factor	2	2	2	2	2	2	

Parameter	Sept. 2005	400kW	700kW	1100kW	1200kW	PD2	
Acceleration loss	8.7	4.5	4.0	4.1	3.8	1.0	%
Efficiency	83	91	91	96	96	97	%
Injection Intensity	5.3	5.0	4.8	4.7	4.6	26.1	$x10^{12}$
Norm. Emittance at Inj	11.4	10.7	10.2	10.0	9.8	38.1	π-mm-mrad
Norm Acceptance at Inj	18.9	21.6	21.4	21.1	21.1	108.4	π-mm-mrad
Momentum Acceptance	0.4	0.4	0.4	0.4	0.4	2.4	%
Misalignment & c.o.d.	10	7	7	7	7	20	mm
F Aperture Width	2.81	2.83	2.82	2.81	2.81	5.93	in
F Aperture Height	1.66	1.63	1.63	1.62	1.62	4.00	in
D Aperture Width	2.06	2.03	2.02	2.01	2.01	5.93	in
D Aperture Height	1.98	1.98	1.97	1.96	1.96	4.00	in

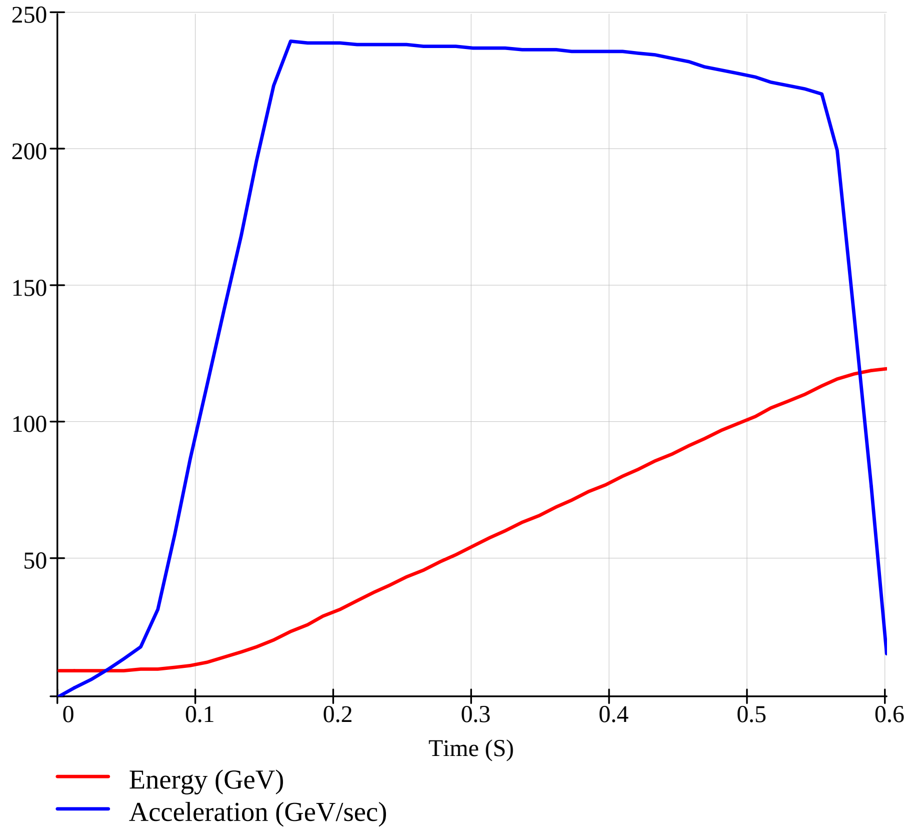
Main Injector RF

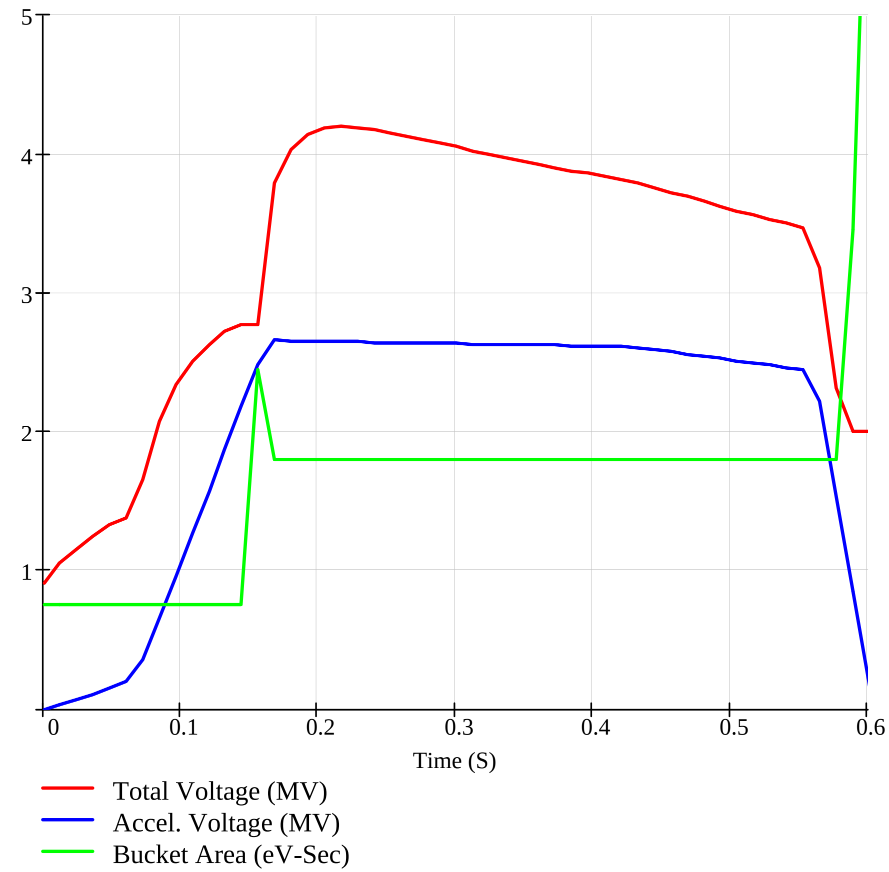
- Beam loading will dominate the operation of the Main Injector RF system for 120 GeV beam powers greater than 700kW.



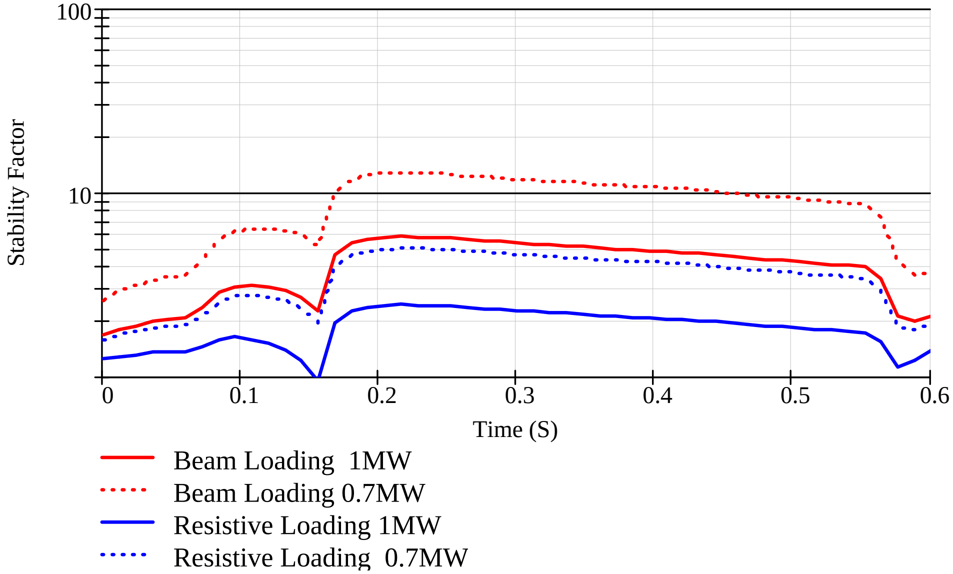


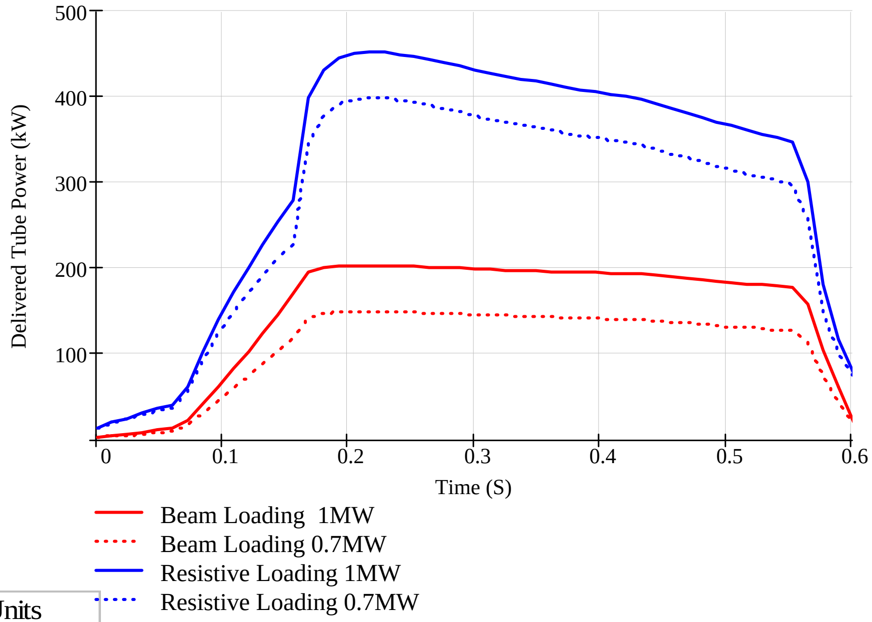
Main Injector RF Curves





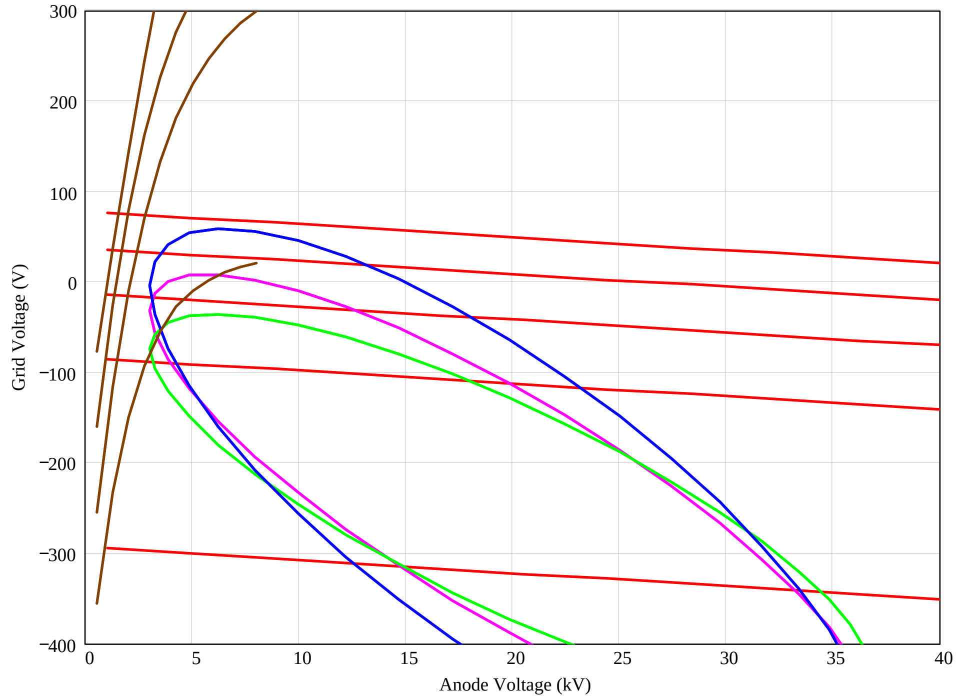
Robinson Stability

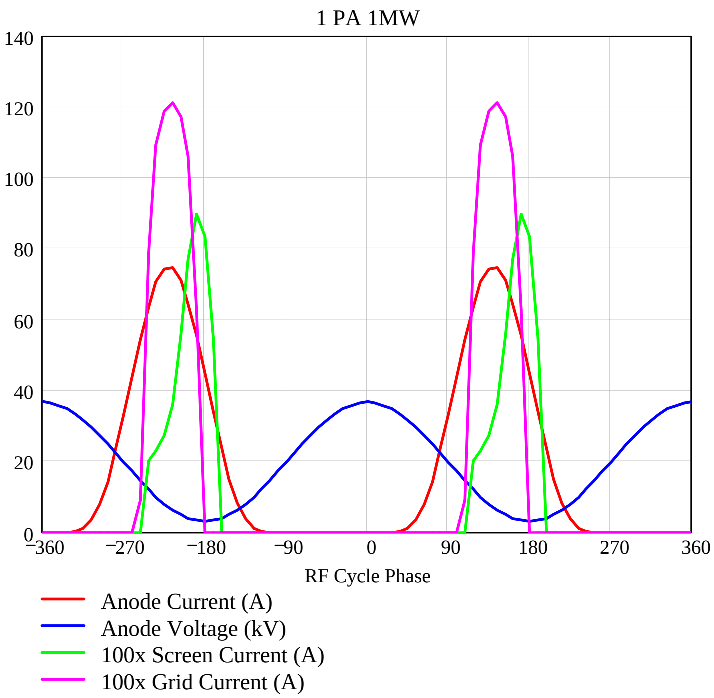




Parameter	Value	Units
RF Frequency	53	MHz
Harmonic	588	
γ_t	21.8	
Ramp time	0.6	S
Cycle Time	1.33	S
Number of Cavities	20	
R/Q	100	Ω
Q	4000	
Coupling	0.1	
Coupler Step-up Ratio	12.5	
Longitudinal Emittance	0.5	eV-S
Ring Filling Factor	0.86	
Beam Loading Compensation	90%	
Resistive Loading	17%	

Power Tetrode Operating Point



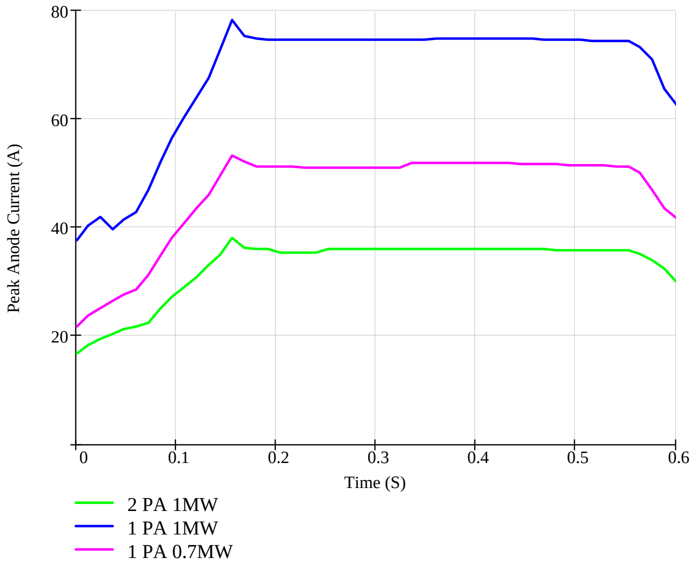


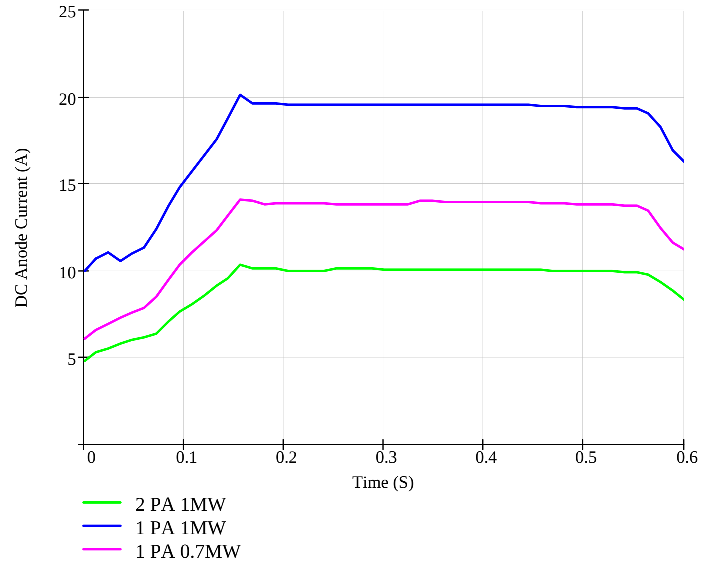
Grid voltage vs. anode voltage at 0.216s. The trajectory for1MW of beam power and a single tube mounted to each cavity is shown in blue, for two tubes mounted to each cavity is shown in green, and for a single tube with 700kW of beam power is shown in magenta. The red traces are for constant anode current of 0.1A, 20A, 40A, 60A, and 80A. The brown traces are constant screen current of

0.2A, 2A, 4A, and 6A.

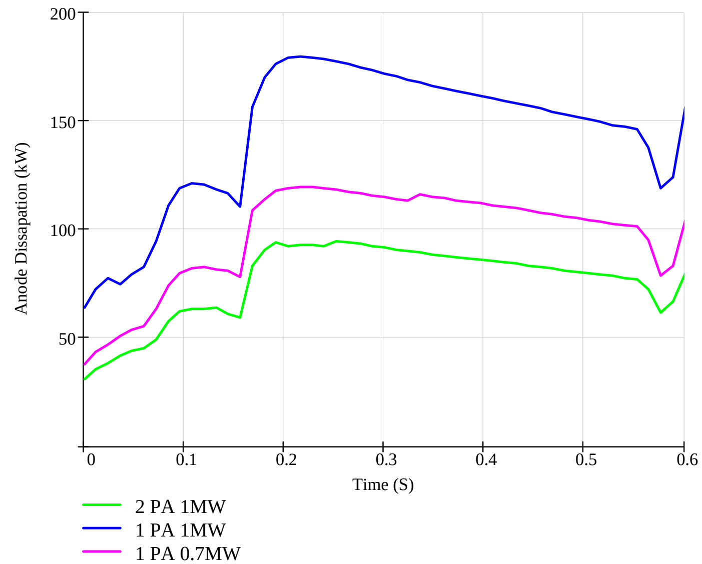
Tube waveforms at 0.216s for a single tube mounted to each cavity. The screen (green trace) and grid (magenta trace) currents are multiplied by 100 to fit on the vertical scale.

Power Tetrode Output





Eimac Y567B Specs.	Maximum	Typical	
Plate Voltage	22	20	kV
Screen voltage	2500	1500	V
Grid voltage	-1500	-800	V
Plate current	20	15.2	Adc
Plate Dissapation	150	84	kW
Screen Dissapation	1750	850	W
Grid Dissapation	500	100	W
Output Power		220	kW



Main Injector Beam Loading Summary

- Active beam loading compensation can achieve larger Robinson stability margins for less RF power than externally loading the RF cavities.
- The requirements for 700kW of beam power for a single tube mounted on each cavity does not exceed normal operating parameters.
- It is possible to accelerate 1 MW of beam power with the current Main Injector RF system driven by a single tube and stay within the maximum rated specifications of the current power tetrode if active beam loading compensation is implemented and the power tetrodes are operated in Class C.
  - However, the peak anode current required by a single tube at 1 MW of beam power is substantially above normal operating experience for reliable operations.
- The two tubes per cavity configuration provides substantial operating margin up to a beam power of 1.5 MW.

Issues

- Once the SNUMI group provides a conceptual design report for slip-stacking in the Recycler, it will begin to further develop the concept of momentum stacking in the Accumulator.
- List of Issues
  - Booster throughput
  - Space charge effects in the Accumulator and Recycler
  - Radiation shielding
  - Beam-loading
  - Transition crossing in the Main Injector
  - Instabilities (electron cloud, coupled bunch, etc.)
  - Etc…

1.1MW Cost Estimate in k$

Description	Cost
AP4 Line Civil	4,500
AP4 Tie In & Installation	1,000
AP3 Modification Civil	3,000
AP3 Tie In & Installation	1,000
Accumulator Shielding	3,000
Accumulator Kickers	1,000
Accumulator 53 MHz RF	600
Accumulator 7.5 MHz RF	600
Accumulator Instrumentation	300
Main Injector RF	12,500
NUMI	3,500
Total	31,000

Summary

- Momentum stacking has much smaller longitudinal emittance dilution than slip stacking and can be used in place of slip stacking to achieve beam powers greater than 700kW
- Because the Accumulator was designed for momentum stacking, the present antiproton production complex can be converted into a multi-stage proton accumulator
  - Accumulator -> Momentum Stacker
  - Recycler -> Box Car Stacker
- The multi-stage proton accumulator can supply enough protons for a 1.1 MW 120 GeV beam for a cost of about $31M
  - The post-Proton Plan Booster should be able to provide the necessary proton flux
  - The present Main Injector RF system could support 1MW but with little operating margin. A two tube system would provide substantial operating margin.